SOIL AND CROP MANAGEMENT

Seedbed Surface Geometry Effects on Soil Crusting and Seedling Emergence

R. L. Baumhardt,* P. W. Unger, and T. H. Dao

ABSTRACT

Seedling emergence is the crucial first step in crop establishment; however, crops frequently must penetrate or lift a thin, dense, soil layer called a crust, which is formed by drop impact or aggregate slaking during rainstorms and sprinkler irrigation. Shaping the soil surface into a small ridge or cap above the seed row may decrease crust strength and improve seedling emergence. Our objectives were to quantify the effects of surface soil geometry (25 mm high by 50 mm wide soil cap without removal) on (i) crust formation and strength, (ii) seedling emergence of selected crops, and (iii) seed zone soil temperature. Sieved (<12 mm) Pullman clay loam soil (Torrertic Paleustoll) was packed into columns (0.30 m wide by 0.45 m long by 0.15 m deep) and planted with grain sorghum [*Sorghum bicolor* (L.) Moench], corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), and wheat (*Triticum aestivum* L.) in rows with a flat or capped surface. Columns were mounted at a 5% slope on a turntable beneath a rotating disk-type rain simulator that applied reverse osmosis water for 1 h at a 48 mm h^{-1} intensity with intercepted or normal drop impact energy. Compared with intercepted (INT) drop impact conditions, normal drop impact (DI) reduced infiltration 22% and formed 4.9 mm thicker crusts that prevented seedling emergence. Thickness, penetration resistance, and seedling emergence of DI soil crusts were unaffected by surface caps. Mean seed zone soil temperatures increased with INT drop impact, but was unaffected by capping. Our test shows that unremoved soil caps did not improve seedling emergence; however, intercepting raindrop impact increases seedling emergence.

TIMELY SEEDLING EMERGENCE is crucial to crop establishment and overall plant vigor, but seedling emergence is frequently governed by soil surface conditions. One such surface condition that acts as a significant barrier to emerging crop seedlings is the presence of a thin, dense, cemented soil surface layer or crust as described in review articles by Kemper and Miller (1974), Awadhwal and Thierstein (1985), and Singer and Warrington (1992). Physical soil crusts develop as raindrops disperse aggregates and detach soil particles that enter and occlude soil surface pores, consequently reducing infiltration and permitting additional sediment deposition in the thickening surface layer or crust. For example, Benyamini and Unger (1984) showed that the developing crust on a Pullman soil rapidly decreased the infiltration rate of simulated rain from 42 to 4 mm h^{-1} in approximately 25 min; however, where wheat straw intercepted drop impact energy or surface applied powdered phospho-gypsum reduced aggregate dispersion the infiltration rate decreased more gradually, requiring approximately 45 min to reach 10 mm h^{-1}, compared with the untreated control.

The study of soil crusts and search for suitable management practices to improve seedling emergence assumes a global scope (Awadhwal and Thierstein, 1985) and highlights the need to improve seedling emergence for greater crop yield (Daba, 1999). Emerging seedlings must either grow through a natural break in the crust or exert a force in excess of the crust strength to fracture or lift the crust (Miller and Gifford, 1974). The force exerted by a germinating seedling varies from 0.15 N for alfalfa to >4.0 N for corn depending on water imbibition and other growth limiting factors such as temperature and seed mass (Goyal et al., 1980). For cotton (*Gossypium hirsutum* L.) seedlings exerting a force of 3.02 to 4.63 N, the corresponding measured axial pressure (or maximum penetrable crust strength) varied from 1.25 to 1.90 MPa. Studies on the southern Great Plains showed that as penetrometer resistance of a crusted soil increased from 0 to 1.0 MPa cotton seedling emergence decreased from 78 to 21% 2 d after planting (Bilbro and Wanjura, 1982). In a study of tillage effects on crusting following sprinkler irrigation, Unger (1984) reported little difference in sorghum seedling emergence or the corresponding overall mean crust strengths of 0.33 to 0.54 MPa. He did report severe crusting following an intense natural rainstorm, which resulted in mean crust strengths that varied from 0.43 to 1.15 MPa and could have depressed seedling emergence.

Seedling emergence through soil crusts may be enhanced with irrigation (when available) that wets and softens the crust, as shown for the Pullman soil where crust strength was reduced by higher water contents (Unger, 1984). Management practices such as applications of straw and phospho-gypsum not only increased infiltration, but also decreased the 10-d mean crust penetration resistance from 0.70 MPa for the control to 0.20 and 0.50 MPa for straw and phospho-gypsum treatments (Benyamini and Unger, 1984). Consequently, the corresponding seedling emergence with straw increased 24% compared with the control. Others have attempted to improve seedling emergence through crusts by managing soil cracking without success (Miller and Gifford, 1974). Alternatively, Kemper and Miller (1974) reported that cotton producers in California control se-

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Abbreviations: CAP, mounded surface treatment; DI, drop impact; FLAT, unmounded surface treatment; INT, intercepted drop impact; RO, reverse osmosis water.

vere crusting effects on seedling emergence by mounding soil in 50 to 75 mm wide by 25 to 50 mm tall hills above the seed during planting. Typically, after germination or the formation of a crust, these small hills or soil caps are removed with tillage, for example, by dragging wide sections of chainlink fence across the field (T.A. Howell, personal communication, 2002). Soil caps also make drop impact angles oblique and may reduce crust strength or promote fracturing along the cap ridge. Retained soil caps permit seedlings to move the crust aside and reduce the amount of force required to penetrate the crust, but no research results were found to substantiate this hypothesis.

Crop production could be made more efficient if seedling emergence through rain-formed soil crusts were improved. Soil capping may reduce crust strength or permit better seedling emergence. The objectives of our study were to quantify the effects of surface soil geometry (soil capping without removal) on (i) crust formation and strength, (ii) seedling emergence of major crops, and (iii) seed zone soil temperature.

MATERIALS AND METHODS

Seedbed surface geometry effects on soil crust formation and seedling emergence of selected crops were quantified in a greenhouse study conducted at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX. Rain with either intercepted (INT) or normal drop impact (DI) was applied to soil columns planted with sorghum, corn, sunflower, and wheat. These eight treatment combinations comprise the whole plot treatment structure as a crop × drop-impact factorial experimental design that was split by superimposing three seed depth–surface geometry treatment combinations (Schabenberger and Pierce, 2002). That is, we randomly assigned the row locations for the combination seeding depth and surface geometry treatments, which included a 35 mm seed depth–flat surface (FLAT-35) and either a 35 or 60 mm seed depth–capped surface (CAP-35, CAP-60) within triplicate main plot soil columns (Fig. 1). Measured treatment effects on cumulative infiltration, crust thickness and penetration resistance, seed zone temperature, and seedling emergence were compared as a mixed model using analysis of variance procedures (SAS Inst., 1988).

Soil columns were prepared using a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) with 0.370 kg kg^{-1} clay, 0.480 kg kg^{-1} silt (Unger and Pringle, 1981), and 0.008 kg kg^{-1} organic C (Schwartz et al., 2002). Soil was collected from the surface 0.15 m of a stubblemulch tilled field maintained in a dryland wheat–sorghum–fallow rotation since 1984 (Jones and Popham, 1997), sieved to pass a 12-mm screen, and air-dried in the greenhouse to a 0.03 ± 0.005 kg kg^{-1} water content. Laboratory columns (0.30 m wide by 0.45 m long by 0.15 m deep) for each main plot treatment combination were packed to a 1.15 ± 0.075 Mg m^{-3} bulk density, which approximates the measured surface, 0 to 0.10 m, field bulk density after stubble mulch tillage (Baumhardt and Jones, 2002). Crops were seeded, longitudinally, in three rows equidistant from each other and the column edge within the center third (0.15 m) of the column using 12 mm spacing for wheat 'TAM 107'[1] (Foundation Seed, College Station, TX) and sorghum 'Pioneer 8699' (Des Moines, IA) or 18 mm spacing for corn 'H-2544' (JC Robinson Seeds, Waterloo, NE) and sunflower 'Dekalb 3875' (Dekalb, IL). The seeding depths of 10 mm in one row and 35 mm for the remaining two rows were randomly assigned. Soil was then added to form a 25 mm tall by 50 mm wide seedbed CAP treatment for the 0.45-m column length above seed rows planted at 10- and 35-mm depths. The resulting seed depth treatments were 35 mm beneath the unmounded control, FLAT-35, surface; or 35 and 60 mm beneath the soil cap peak to obtain the CAP-35 and CAP-60 treatments.

Seed zone temperature and the surface crust strength were measured along the unplanted portions of the rows. Planned rain formed crust strength measurements included both penetration resistance and the tractive force or tension required to fracture a soil crust by withdrawing a 10 mm diameter disc. Preliminary soil column preparation was required for the triplicate crust tension measurements of the flat or capped soil surfaces. Modified roofing nails having 10 mm diameter heads were placed 25 mm below the flat or capped soil surface (Fig. 2). The hooked tip served as connection point for tension measurements taken normal to the flat surface and through the soil cap peak. From "spot checks" comparing nail depth

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS.

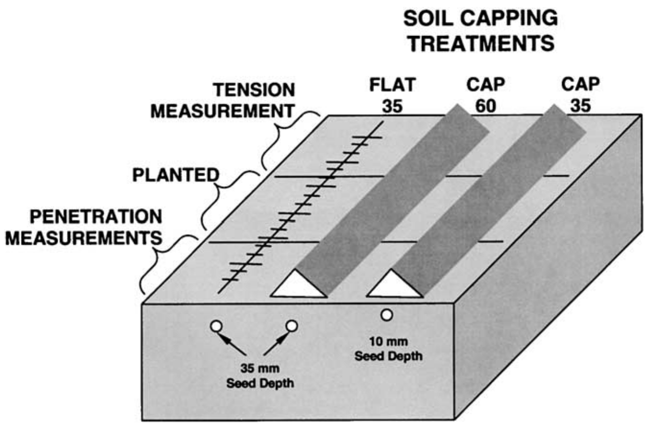

Fig. 1. Diagram of a mainplot seedbed with the superimposed 10 or 35 mm seed depth by surface capping split treatments, which include seed placement 35 mm beneath a flat surface (FLAT-35) and 35 or 60 mm beneath a capped surface (CAP-35, CAP-60). In the field, soil caps are removed by tillage if rain forms a crust capable of interfering with seedling emergence.

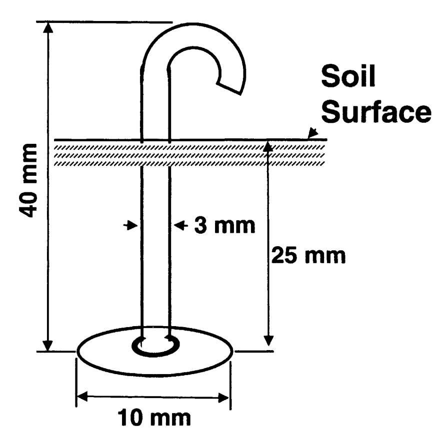

Fig. 2. Soil crust strength was determined by measuring both the tractive force required to pull a modified roofing nail placed 25 mm below the soil surface through a dry crust and compressive force to fracture a moist or dry crust using a calibrated handheld penetrometer.

after rain with the antecedent 25 mm nail installation depth we estimated a small 3.6 mm (SE 0.4 mm) reduction in soil cap height due to the combined effects of erosion and consolidation, but no measurements of treatment effects on microtopography were taken.

Rain Simulation

Prepared soil columns were mounted at a 5% slope on a turntable beneath a rotating disk type rain simulator (Baumhardt and Wendt, 1988). Rain simulations used reverse osmosis (RO) water (EC of 0.03 ± 0.005 dS m^{-1}) in lieu of rainwater because of their similar dispersive characteristics (Baumhardt et al., 1992). Rain simulations were 1 h duration at 48 mm h^{-1} application intensity, which approximated the average rain intensity of a 1-h storm for this region (Frederick et al., 1977) and was sufficiently high to produce runoff for both intercepted and normal drop impact treatments. Simulated rain achieved an impact energy of 22 J mm^{-1} m^{-2}, which is approximately 80% of natural rainfall (Morin et al., 1967). For the intercepted drop impact treatments, soil columns were covered with an energy absorbing barrier made of window screen as described by Baumhardt et al. (1990). Cumulative infiltration was calculated as the difference between the rain application and measured cumulative runoff depths.

Measurements

After simulated rain application, soil columns were moved to tables in a greenhouse that was maintained at a suitable temperature for seed germination (mean 24°C, SD 8.1°C, median 18°C). Seed zone soil temperature determined with twisted and soldered copper-constantan wire thermocouples inserted to the seed placement depth was electronically measured every 15 s and recorded on 15-min intervals by a data logger (Model CR-7, Campbell Scientific, Logan, UT). Seedling emergence of leafs through the crusted soil was observed daily; however, only the final emergence observations were analyzed as an indirect measure of soil crust strength. Direct measurements of the soil crust strength were determined within each treatment at six sample locations along the center of the unplanted rows for both capped and flat seed bed surfaces 1 d (INITIAL) and 10 d (FINAL) after rain application. That is, crust strength was the penetration resistance or required force applied vertically downward to fracture the soil crust using a 4.76-mm diameter flat point handheld penetrometer (Model 719-5 MRP, John Chatillon & Sons, Kew Garden, NY). The handheld penetrometer was also used to measure the tension or tractive force required to withdraw previously installed 10-mm diameter discs through the soil crust. After the FINAL crust strength measurements, we estimated the soil crust thickness above the seedlings in three representative flat and capped sites. Crust thickness was determined macroscopically from the presence of disturbed soil aggregates, sediment bedding planes, and reduced porosity as compared with the underlying unconsolidated bulk soil.

RESULTS AND DISCUSSION

Crust Formation

Conversion of the soil surface into a dense and less conductive crust typically reduces rain infiltration and increases penetration resistance as reported by Unger (1984), Dao (1993), Shainberg et al. (1992), and others. In our test, measured infiltration of simulated rain decreased as a result of raindrop impact that formed soil surface crusts. That is, cumulative infiltration ±1 SD after 1 h decreased 22% from 37.6 ± 3.3 mm with intercepted drop impact (INT) compared with 29.0 ± 2.3 mm for the normal drop impact (DI) treatment. This reduction in infiltration rate was attributed to drop impact that decreased pore size and continuity in the surface soil crust. Where rain drop impact was intercepted, the soil crusts were formed primarily by dispersion and slaking of surface aggregates as described by Baumhardt et al. (1992). The soil crusts formed without drop impact sustained less extensive changes in the soil surface pore structure; thus, producing less developed and more conductive soil crusts that permitted a higher infiltration rate.

Differences in pore structure of the surface and underlying bulk soil defined soil crusts layers of variable thickness. Our measured soil crust thickness, listed in Table 1, averaged 10.9 mm with the DI treatment compared with 6.0 mm for the INT drop impact treatment. Impacting raindrops increased fracturing of soil aggregates and detachment of soil particles and consequently increased crust thickness an average of 5 mm, or about 80%, compared with crusts formed with INT drop impact. We attributed thinner INT crusts formation to rain dispersion of surface aggregates. The measured difference in crust thickness between the flat and "capped" soil surface geometries averaged <1.0 mm and was not significant ($P = 0.05$) regardless of drop impact. These data show that the more oblique drop impact angle of capped soil surface did not reduce aggregate detachment compared with the flat soil surface. Where raindrop impact was intercepted, drainage of rainwater from the sloping soil caps did not significantly diminish the thickness of crusts formed by aggregate dispersion.

Crust strength determined as penetration resistance measured 1 d (INITIAL) and 10 d (FINAL) after rain application varied within an overall 0.20 to 0.60 MPa range (Table 1). Our crust strength values were consistent with previously reported field measurements of crust strength for a Pullman soil (Unger, 1984). The INITIAL crust resistance of the 0.38 MPa with DI averaged approximately 80% more than the 0.21 MPa crust strength measured for the INT treatment (Table 1). Again, the surface geometry treatments produced a negligible difference between the mean INITIAL crust strength for capped (CAP) 0.29 MPa compared with crust strength of 0.31 MPa for the flat soil surface (FLAT). These data show that drop impact resulted in more extensive crust formation and produced significantly greater penetration resistance; however, crusts were unaffected by the soil surface geometry.

The FINAL crust penetration resistance determined 10 d after rain application was approximately 50% greater than observed for the INITIAL crust strength (Table 1). Loss of water from the drying crust focuses increased surface tension forces along the receding water meniscus that, consequently, consolidates soil particles, reduces pore space, and bonds the surface layer into a harder crust (Kemper et al., 1974). However, the effects of drop impact and surface geometry treatments produced similar crust strength responses for both INI-

Table 1. Rain drop impact and soil surface geometry effects on crust thickness and strength. Penetration resistance was measured 1 d (INITIAL) and 10 d (FINAL) after rain application and crust tension resistance was determined after 10 d.

Treatments†	Crust thickness	Penetration resistance Initial	Penetration resistance Final	Tension resistance Final
	mm	MPa		
DI-FLAT	10.9	0.40	0.60	0.014
DI-CAP	11.0	0.37	0.52	0.012
INT-FLAT	6.4	0.21	0.31	0.014
INT-CAP	5.5	0.20	0.31	0.008
LSD‡	1.4	0.05	0.07	0.002

† Treatments are drop impact (DI) and intercepted drop impact (INT) rain applications to soil with level (FLAT) or mounded (CAP) surface geometry.
‡ The least significant difference (LSD) is reported at the ($P < 0.05$) level.

TIAL and FINAL observations. That is, the DI crust strength of 0.56 MPa was approximately 80% larger than 0.31 MPa with INT drop impact. As observed in the INITIAL crust strength, the flat or capped surface geometry treatments resulted in no difference in FINAL observed crust strength. Residue can be managed to intercept raindrop impact and also delay crust drying; thus, potentially increasing seedling emergence.

We measured the tractive force, or tension, required to fracture the soil crusts immediately after determining the FINAL penetrometer resistance (Table 1). The measured tension resistance of the crust varied from 2 to 5% of the penetration resistance. Unlike penetrometer soil crust measurements that also integrate pressure applied against the underlying soil, the applied tension force typically lifted or pushed the crust aside rather than fracturing the crusted layer. Soil crust resistance to tension did not consistently vary with treatments, although the force needed to lift the soil crust may more accurately duplicate those forces applied by seedlings during emergence.

Seed Zone Temperature

Relative comparisons of soil depth, raindrop impact, and seedbed surface geometry effects on the seed zone soil temperatures were determined after rain application. Typical daily soil temperature fluctuations are shown for 2 consecutive days (Fig. 3) that have similar minimum temperatures regardless of the measurement depth or surface geometry treatment and maximum temperatures that range from 30 to 37°C depending on treatments. Consistent with this example, the greatest soil temperature fluctuations, i.e., difference in maximum and minimum temperatures, were measured 35 mm below the cap peak because of its near proximity to the larger exposed surface area. Soil temperatures measured at 35 mm below the flat soil surface and at 60 mm below the 25 mm tall cap peak were similar as a result of nearly identical thermocouple placement depths below the flat soil surface. However, temperatures measured 60 mm below the cap exhibited a small time lag or shift later than those measured 35 mm below the flat soil surface due to the additional soil forming the cap (Fig. 3). Maximum soil temperatures measured

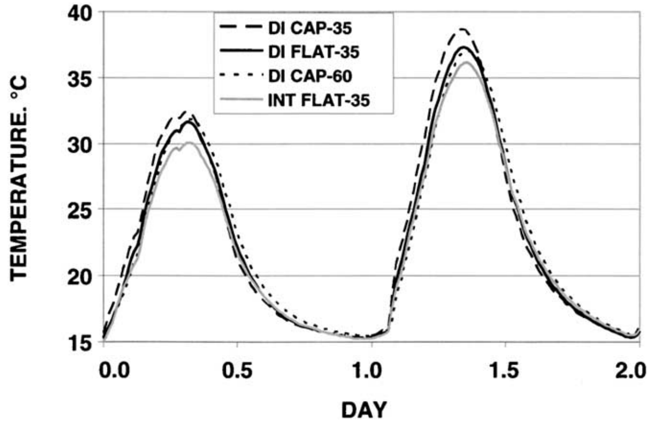

Fig. 3. Representative soil temperature data showing typical diurnal fluctuations over a 2-d period. Soil temperature was measured 35 mm beneath a flat surface for intercepted drop impact (INT FLAT-35) and, for normal drop impact (DI), measured 60 mm beneath the soil cap peak (CAP-60), and 35 mm beneath the capped (CAP-35) or flat (FLAT-35) soil).

in the INT treatment combinations were about 1.5°C less than the corresponding DI treatments (e.g., INT FLAT-35), which was attributed to greater soil water contents that moderated temperature fluctuations.

Drop impact and surface geometry treatment effects on daily minimum, mean, and maximum seed zone soil temperatures measured during the 10 d post rain application germination period are shown in Table 2. Generally, higher minimum and lower maximum soil temperatures were observed under thinner crusts formed by the INT drop impact compared with normal DI treatments. Because the less dense and more conductive INT crusts increased both cumulative infiltration and the related soil water content, seed zone soil temperature fluctuations, i.e., the difference between minimum and maximum soil temperatures were moderated. The significantly higher mean soil temperature for INT compared with DI treatments was likewise attributed to the higher soil water content following increased infiltration through weaker crusts.

Table 2. Rain drop impact and soil surface geometry effects on the minimum, maximum, and mean seed zone soil temperature. Seed zone depths were 35 mm below the flat surface (FLAT-35) compared with 60 and 35 mm below the 25 mm tall capped surface (CAP-60, CAP-35).

Treatments†	Seed zone soil temperature FLAT-35	CAP-60	CAP-35	Geometry effects
	Minimum, °C			
DI	12.8	12.9	12.8	nd‡
INT	13.3 a	13.3 a	12.9 b	**
Impact effects	**	**	nd	LSD§ = 0.29
	Mean, °C			
DI	21.0	20.8	21.2	nd
INT	21.8	21.9	22.0	nd
Impact effects	**	**	**	LSD§ = 0.52
	Maximum, °C			
DI	42.0 b	40.7 c	44.3 a	**
INT	40.5 b	40.1 b	43.0 a	**
Impact effects	**	nd	**	LSD§ = 1.22

† Treatments are drop impact (DI) and intercepted drop impact (INT) rain applications to flat or capped surfaces.
‡ nd = no significant difference.
§ The least significant difference (LSD) is reported at the ($P < 0.05$) level.

Mean soil temperatures during the 10 d crop germination and emergence period varied from 20.8 to 22.0°C (Table 2) and were consistent with the long-term average soil temperatures recorded during mid-June at Bushland. These temperatures were unaffected by seed zone depth or the flat and capped surface conditions. Similarly, minimum soil temperatures varied little among all depth and surface geometry treatments, except for CAP-35. Minimum seed zone soil temperatures of FLAT-35 or deeper CAP-60 treatments differed significantly from CAP-35, probably because of the greater surface area and surface proximity to the seed zone. The maximum soil temperature measured during this 10-d period decreased in order from the CAP-35, to FLAT-35, and then CAP-60. The higher peak temperature was again attributed to proximity between the seed zone and the soil surface and the greater exposed surface area with caps that promoted loss of soil water that moderated soil heat flux. Although our data show that capping consistently affected maximum seed zone temperature, the increased soil water content in INT drop impact moderated soil temperature regardless of surface geometry and would likely benefit seedling emergence in early planted crops.

Seedling Emergence

Crop seedlings integrate the treatment drop impact and surface geometry effects on soil crust strength in terms of a dependent seedling emergence rate. We compared the emergence of both large-seed crops, corn and sunflower, and small-seed crops, wheat and sorghum, through crusts formed under combinations of drop impact and soil surface geometry treatments. In our test, DI crusts were sufficiently strong to prevent seedling emergence of all tested crops regardless of the surface geometry treatment. This observation led to destructive sampling of all columns for the purpose of confirming seed germination and quantifying the potential number of emerging seedlings. Although no seedlings emerged through DI crusts, virtually all seeds had germinated. Seedling emergence determined as a percentage of the germinated seed for each crop 10 d after rain application was reduced significantly ($F = 707.4$, $P < 0.01$) by raindrop impact. Our results show that the sloping soil cap surface geometry did not diminish the formation of strong soil crusts by a more oblique raindrop impact angle. Expected seedling emergence following a crusting rain would be uniformly greater if the soil caps had been physically removed during seed germination as is typically done with caps. The necessity of physically removing soil caps during germination to increase seedling emergence through rain-formed crusts may contribute to increased production risk when crust removal is delayed.

In contrast to seedling emergence through DI crusts, the depositional INT soil crusts formed, principally, by dispersion and slaking of soil aggregates reduced seedling emergence that varied by crop. That is, mean seedling emergence through INT soil crusts was 72.2% for sorghum, 75% for wheat, 80.6% for corn, and 91.7% for sunflower. Seedling emergence of the small seed sorghum and wheat crops was similar, and noticeably less than the large seed corn and sunflower crops; however, only the difference between sorghum and sunflower was significant ($P = 0.05$). As noted by Goyal et al. (1980), seedlings of larger seeded crops can exert more force from normal imbibition and apply greater pressure to emerge through a crust. Seedling emergence of either large or small seeded crops did not benefit from the capped surface geometry compared with flat soil and resulted in no significant crop by geometry interaction. Seedling emergence data for the different crops were pooled for comparison of surface geometry effects.

Comparisons of seedling emergence through depositional crusts, that is, with INT drop impact, revealed trends that emergence improved as the surface geometry treatments decreased seed depth. That is, the resulting seedling emergence, although not significantly different ($F = 2.52$, $P = 0.09$), were lowest for surface geometry with a seed placement depth of 60 mm below the cap-peak, CAP-60. The CAP-60 seedling emergence was 70.4% compared with 84.4% for flat soil and 82.6% for the CAP-35 treatments with seed depths of 35 mm. As previously noted, the soil CAP treatment did not increase seedling emergence through the thicker and stronger crusts formed with raindrop impact on the Pullman soil. Our data show that soil caps left in place do not benefit seedling emergence compared with flat seedbed geometry, and may reduce emergence unless the crusted soil cap is physically removed.

SUMMARY AND CONCLUSIONS

The effects of raindrop impact and soil surface geometry on crust thickness, penetration resistance, seed zone temperature, and seedling emergence were evaluated for a Pullman clay loam. Soil crusts formed with raindrop impact were significantly thicker than crusts formed with intercepted drop impact. Similarly, penetration resistance increased with DI crusts while infiltration and seedling emergence decreased. The soil surface cap geometry that produced a more oblique drop impact angle did not decrease measured crust thickness, penetration resistance, or seedling emergence for DI crust formation. Surface capping decreased mean measured maximum soil temperature in order of CAP-35, FLAT-35, and CAP-60 because of proximity between the seed zone and the soil surface; however, mean and minimum soil temperatures were unaffected by the surface geometry ($P = 0.05$).

Under the conditions of our test, we conclude that intercepting raindrop impact was the overwhelming best treatment to improve seedling emergence. Tillage practices that retain crop residues at the soil surface provide a natural barrier for intercepting raindrop impact, which reduces crust strength (Unger, 1984; Lopez et al., 2000) and increases seedling emergence (Ozpinar and Isik, 2004). Baumhardt and Lascano (1999) concluded that, compared with conventional bare-soil tillage, the limited residue retained with no tillage intercropped wheat prevented crust formation, improved cotton seedling emergence, and negated replanting. Our data show that soil capping without removal did not reduce crust formation or strength, increase seedling emergence, or increase the mean seed zone soil temperature on a clay loam soil such as the Pullman. Tillage to remove crusted soil caps appears to be necessary for promoting seedling emergence.

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